

U.S. DEPARTMENT OF COMMERCE, PATENT AND TRADEMARK OFFICE		DATE: <b>January 3, 2002</b>
<b>TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371</b>		U.S. APPLN. NO. (if known): <b>100192751</b>
INTERNATIONAL APPLICATION NO.: <b>PCT/JP00/04301</b>	INTERNATIONAL FILING DATE: <b>JUNE 29, 2000</b>	PRIORITY DATE CLAIMED: <b>JULY 7, 1999</b>
TITLE OF INVENTION: <b>DIAMOND ULTRAVIOLET LUMINESCENT ELEMENT</b>		
APPLICANT(S) FOR DO/EO/US: <b>Kenji HORIUCHI, Takefumi ISHIKURA, Satoshi YAMASHITA, Aki KAWAMURA, Kazuo NAKAMURA, Kenichi NAKAMURA and Takahiro IDE</b>		
Applicant hereby submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:		
<p>1. <u>XX</u> This is a <b>FIRST</b> submission of items concerning a filing under 35 U.S.C. 371.</p> <p>2. <u>    </u> This is a <b>SECOND</b> or <b>SUBSEQUENT</b> submission of items concerning a filing under 35 U.S.C. 371.</p> <p>3. <u>XX</u> This express request to begin national examination procedures (35 USC 371(f)) at any time rather than delay examination until the expiration of the time limit set in 35 USC 371(b) and PCT Articles 22 and 39(1).</p> <p>4. <u>XX</u> A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.</p> <p>5. <u>XX</u> A copy of the International Application as filed (35 U.S.C. 371(c)(2)):</p> <p style="margin-left: 40px;">a. <u>    </u> is transmitted herewith (required only if not transmitted by the International Bureau).</p> <p style="margin-left: 40px;">b. <u>XX</u> has been transmitted by the International Bureau.</p> <p style="margin-left: 40px;">c. <u>    </u> is not required, as the application was filed in the United States Receiving Office (RO/US).</p> <p>6. <u>XX</u> A translation of the International Application into English (35 U.S.C. 371(c)(2)).</p> <p>7. <u>XX</u> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))</p> <p style="margin-left: 40px;">a. <u>    </u> are transmitted herewith (required only if not transmitted by the International Bureau).</p> <p style="margin-left: 40px;">b. <u>    </u> have been transmitted by the International Bureau.</p> <p style="margin-left: 40px;">c. <u>    </u> have not been made; however, the time limit for making such amendments has NOT expired.</p> <p style="margin-left: 40px;">d. <u>XX</u> have not been made and will not be made.</p> <p>8. <u>    </u> A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).</p> <p>9. <u>XX</u> An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).</p> <p>10. <u>    </u> A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).</p> <p><b>ITEMS 11. TO 16. BELOW CONCERN OTHER DOCUMENT(S) OR INFORMATION INCLUDED:</b></p> <p>11. <u>    </u> An Information Disclosure Statement under 37 CFR 1.97 and 1.98.</p> <p>12. <u>XX</u> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included. ASSIGNEE NAME AND ADDRESS: <b>TOKYO GAS CO., LTD., Tokyo, Japan</b> <b>Please publish the assignee data with the application.</b></p> <p>13. <u>XX</u> A <b>FIRST</b> preliminary amendment. <u>    </u> A <b>SECOND</b> or <b>SUBSEQUENT</b> preliminary amendment</p> <p>14. <u>    </u> A substitute specification.</p> <p>15. <u>    </u> A change of power of attorney and/or address letter.</p> <p>16. <u>XX</u> Other items or information: 9 sheets of drawings and international search report.</p>		

U.S. APPLICATION NO. (if known) <b>10/019275</b>	INTERNATIONAL APPLICATION NO. <b>PCT/JP00/04301</b>	DATE: <b>January 3, 2002</b>
17. <input checked="" type="checkbox"/> The following fees are submitted:  <b>Basic National Fee (37 CFR 1.492(a)(1)-(5):</b> Search Report has been prepared by the EPO or JPO: ..... \$890.00  International preliminary examination fee paid to USPTO (37 CFR 1.482) ..... \$710.00  No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2)) ..... \$740.00  Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... \$1040.00  International preliminary examination fee (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) ..... \$100.00  <div style="text-align: right;"><b>ENTER APPROPRIATE BASIC FEE AMOUNT = \$ 890.00</b></div>		<div style="display: flex; justify-content: space-between;"> <div style="width: 60%; border-bottom: 1px solid black; padding-bottom: 5px;"> <b>CALCULATIONS</b> </div> <div style="width: 35%; border-bottom: 1px solid black; padding-bottom: 5px;"> <b>PTO USE ONLY</b> </div> </div>
Surcharge of <b>\$130.00</b> for furnishing the oath or declaration later than __ 20 30 months from the earliest claimed priority date (37 CFR 1.492(e)).		
CLAIMS	NUMBER FILED	NUMBER EXTRA
TOTAL	19 -20 =	X \$ 18.00
INDEPENDENT	1 - 3 =	X \$ 84.00
Multiple dependent claims(s) (if applicable)		+ \$280.00
<b>TOTAL OF ABOVE CALCULATIONS =</b>		<b>\$ 890.00</b>
Reduction by 1/2 for filing by small entity, if applicable. (Note 37 CFR 1.9, 1.27, 1.28).		
<b>SUBTOTAL =</b>		<b>\$ 890.00</b>
Processing fee of <b>\$130.00</b> for furnishing the English translation later than __ 20 __ 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +		
<b>TOTAL NATIONAL FEE =</b>		<b>\$ 890.00</b>
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). <div style="text-align: right;"><b>\$40.00 per property +</b></div>		<b>\$ 40.00</b>
<b>TOTAL FEES ENCLOSED =</b>		<b>\$ 930.00</b>
Amount to be:		
_____ refunded		\$ _____
_____ charged		\$ _____

ATTORNEY'S DOCKET NO: 011779

U.S. APPLICATION NO. (if known) <b>10/019275</b>	INTERNATIONAL APPLICATION NO. <b>PCT/JP00/04301</b>	DATE: <b>January 3, 2002</b>
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a. ☒ A check in the amount of \$ 930.00 to cover the above fees is enclosed. (\$890.00 for basic filing fee and \$40.00 for assignment recordation fee). (This paper is filed in triplicate)


b. ☐ Please charge my Deposit Account No. 01-2340 in the amount of \$     to cover the above fees. (A duplicate copy of this sheet is enclosed.)

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 01-2340.

**NOTE:** Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed to request that the application be restored to pending status.

**Send All Correspondence To:**

  
**23850**  
PATENT TRADEMARK OFFICE

  
SIGNATURE  
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**PATENT**

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

In re application of: **Kenji HORIUCHI et al.**

Serial No.: **Not Yet Assigned**  
**(PCT/JP00/04301)**

Filed: **January 3, 2002**

For: **DIAMOND ULTRAVIOLET LUMINESCENT ELEMENT**

**PRELIMINARY AMENDMENT**

Commissioner for Patents  
Washington, D.C. 20231

January 3, 2002

Sir:

Prior to the calculation of the filing fees of the above application, please amend the application as follows:

**IN THE CLAIMS:**

Please amend the following claims as follows:

3. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said diode-structure diamond ultraviolet light-emitting device comprises a pn junction.

4. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein both said diamond crystals are high-quality crystals including only a minute amount of impurity other than the dopant.

Kenji HORIUCHI et al.

Docket No. 011779

5. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said n-type diamond crystal is a diamond crystal doped with phosphorous.

6. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said n-type diamond crystal is a diamond crystal doped with sulfur.

7. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said n-type diamond crystal is a diamond crystal grown by a chemical vapor deposition method.

8. (Amended) A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 7, wherein said p-type semiconductor diamond crystal is a diamond crystal doped with boron.

10. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said p-type semiconductor diamond crystal is a crystal synthesized by a high temperature and high pressure synthesis method.

12. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said p-type semiconductor diamond crystal is a diamond crystal grown by a chemical vapor deposition method.



Kenji HORIUCHI et al.

Docket No. 011779

19. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 16, wherein an electrode is formed on the exposed surface of said first diamond layer grown by the chemical vapor deposition method.

Kenji HORIUCHI et al.

Docket No. 011779

REMARKS

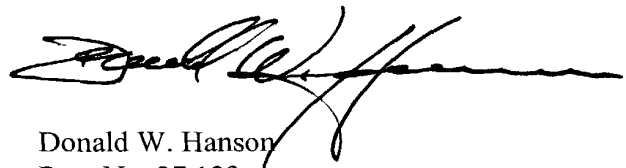
The above amendment is believed to place the claims in proper condition for examination.  
Early and favorable action is awaited.

Attached hereto is a marked-up version of the changes made to the claims by the current amendment. The attached page is captioned "Version with markings to show changes made."

In the event there are any additional fees required, please charge our Deposit Account No. 01-2340.

Respectfully submitted,

ARMSTRONG, WESTERMAN & HATTORI, LLP



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Kenji HORIUCHI et al.

Docket No. 011779

15. (Amended) A diode-structure diamond ultraviolet light-emitting device according to ~~any one of claims 1 through 11~~ claim 1, said device comprising a p-type semiconductor diamond crystal synthesized by ~~the~~ a high temperature and high pressure synthesis method, and a n-type diamond crystal grown on said p-type semiconductor diamond crystal by ~~the~~ a chemical vapor deposition method.

16. (Amended) A diode-structure diamond ultraviolet light-emitting device according to ~~any one of claims 1 through 9 or claims 12 through 15~~ claim 1, wherein a first diamond crystal grown by ~~the~~ a chemical vapor deposition method is formed on a diamond substrate, and a second diamond crystal grown by ~~the~~ a chemical vapor deposition method is further formed thereon.

18. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 16 ~~or 17~~, wherein said second diamond layer grown by the chemical vapor deposition method is grown selectively on said first diamond layer grown by the chemical vapor deposition method.

19. (Amended) A diode-structure diamond ultraviolet light-emitting device according to claim 16, ~~17 or 18~~; wherein an electrode is formed on the exposed surface of said first diamond layer grown by the chemical vapor deposition method.

g/pv

## DIAMOND ULTRAVIOLET LUMINESCENT ELEMENT

## FIELD OF THE INVENTION

The present invention relates to a diamond ultraviolet light-emitting device having a diode structure for realizing the free exciton recombination radiation utilizing a diamond grown by the chemical vapor deposition method, capable of being applied to the field of optical information read/write processing, photolithography, optical processing, phosphor excitation light source and the like.

## SUMMARY OF THE INVENTION

Owing to its short wavelength, ultraviolet light can be utilized for micro fabrication, and there are various demands for ultraviolet technology such as improving the recording density of the optical read/write processing or improving the packaging density in the semiconductor devices.

A dutrium lamp and an excimer laser are two examples of the light source in the ultraviolet wavelength region. However, according to the dutrium lamp, the ultraviolet light emission has low efficiency and low brightness. As for the excimer lasers utilizing gas, the device is dangerous and inconvenient to handle since it is large and requires cooling water and halogen. Therefore, the conventional ultraviolet light sources have various inconveniences for actual applications.

On the other hand, diamond is also known as material that

emits ultraviolet light. The diamond ultraviolet light-emitting device is small in size, highly efficient, very bright, and is advantageously safe to use.

Especially in the case of a light emitting device having a diode structure such as a pn junction, the luminous efficiency is improved even further. This is because for example in a pn junction, an energy barrier exists at the interface between the p-type layer and the n-type layer that stores the carrier contributing to the light emission. The light emitting portion is approximately the border between the p-type layer and the n-type layer.

The conventional diamond light-emitting device is disclosed for example in (1) Japanese Patent Laid-Open Publication No. 4-240784 (240784/92), (2) Japanese Patent Laid-Open Publication No. 7-307487 (307487/95), and (3) Japanese Patent Laid-Open Publication No. 5-152604 (152604/93).

According to these conventional diamond light-emitting devices, the diamond forming the p-type layer is doped with boron, and the diamond forming the n-type layer is doped with lithium, phosphorous and the like, and they realize a diode property. However, according to the ultraviolet radiation of the conventional diamond light-emitting device, light emission was caused mainly by impurities or lattice defects, and the free exciton recombination radiation intrinsic to diamond and having a short wavelength is not dominant.

There are explanations on the free exciton recombination

radiation in the above-mentioned publications, but they are merely explanations on the result of radiating electron beams to the diamond from the exterior and measuring the light emission by the cathode luminescence (CL) method so as to confirm the properties of the diamond.

Japanese Patent Laid-Open Publication No. 4-240784 discloses an ultraviolet light-emitting device formed by providing a boron-doped p-type diamond crystal semiconductor layer on a monocrystal diamond substrate, forming on top an undoped diamond film, and further forming thereon a phosphorous-doped n-type diamond crystal semiconductor layer, and an ultraviolet light-emitting device forming on one surface of a p-type monocrystal substrate a diamond film having both boron and phosphorous doped thereto, and further forming on the diamond film a phosphorous-doped diamond film. According to the publication, the former ultraviolet light-emitting device has an ultraviolet radiation peak at 260 nm caused by boron-related band radiation, and the latter device has an ultraviolet radiation peak at around 400 nm, and the disclosure aims at providing a solid-state ultraviolet light-emitting device driven simply by current injection, but according to the above devices of the prior art, ultraviolet radiation of 235 nm caused by the free exciton recombination radiation resulting from current injection is not dominant.

Further, Japanese Patent Laid-Open Publication No. 7-307487 discloses a short-wavelength light-emitting device comprising

Japanese Patent Laid-Open Publication No. 5-152604 discloses a diamond semiconductor device formed by chemical vapor deposition method and including a pn junction, wherein in embodiment 11, a diamond semiconductor device is disclosed where the p-type semiconductor region includes boron as the impurity and the n-type semiconductor region includes lithium as the impurity. When voltage is applied thereto, the semiconductor device emits light having a peak at 440 nm. However, the publication does not refer to the ultraviolet radiation of the free exciton recombination radiation caused by current injection.

4

wherein the device comprises forming on a low-resistance silicon substrate a p-type semiconductor diamond layer, and an insulating diamond layer thereabove, further forming an ohmic electrode on a portion of the surface of the p-type semiconductor diamond layer, and a surface electrode on the insulating diamond layer, wherein the formed light-emitting device emits greenish white light. The publication further discloses forming on a low-resistance silicon substrate an n-type semiconductor diamond layer, and forming an insulating diamond layer thereabove, forming a back electrode on the back surface of the n-type semiconductor diamond and a surface electrode on the insulating diamond layer, wherein the light-emitting device emits pale blue light. However, there is no description in the publication that the semiconductor light-emitting device emits ultraviolet resulting from free exciton recombination radiation.

When considering a diode-structure diamond ultraviolet light-emitting device, the light emission caused by impurities/defects has a longer wavelength compared to the intrinsic light emission as disclosed in Japanese Patent Laid-Open Publication No. 4-240784 or No. 7-307487, and therefore it is not desirable as a short-wavelength light-emitting device. Furthermore, in order to improve the emission intensity, it is necessary to introduce high density of defects or high concentration of impurity to the diamond crystal, and as a result, the quality of the crystal is deteriorated and the intensity of the ultraviolet light emission is reduced. Even further,



the emission peaks at various wavelengths induced by the introduction of impurities/defects consumed a portion of the injected energy, deteriorating the efficiency of even the useful ultraviolet radiation. Due to these reasons, the light emission caused by impurities or defects is not practical for the mechanism of a current-injection light-emitting device.

On the other hand, the free exciton recombination radiation is a light emission intrinsic to each material, and generally has the shortest wavelength and a high density of states compared to the variety of other light emissions obtained from the material, so it is most preferable for realizing a practical bright light-emitting device. As for diamond, the intrinsic spectrum related to the free exciton recombination radiation is studied using analyzing methods such as the CL method. The energy of the free exciton of diamond at room temperature corresponds to a wavelength of 229 nm, but actually, light emissions called the phonon side band group that appear near 235 nm, 242 nm, 249 nm and 257 nm are mainly observed. In general, all of the above are inclusively called "free exciton recombination radiation", but the light that is most preferable in an ultraviolet light-emitting device is the light having energy around 235 nm, and in the present specification, this specific light emission is called the "free exciton recombination radiation".

#### DISCLOSURE OF THE INVENTION

As explained, the conventional diamond ultraviolet

light-emitting device utilizes a light-emitting diamond crystal layer that is poor in quality and containing a lot of impurities or defects. Therefore, when a diamond crystal is used to realize a current-injection light-emitting device, it is impossible to obtain sufficient radiation intensity by the free exciton recombination radiation that is the most advantageous radiation in practical use.

For example, Japanese Patent Laid-Open Publication No. 4-240784 discloses a diamond light-emitting device with a p-i-n diode structure that has a peak at a wavelength of 400 nm and emits light having a wide range of wavelength from 300 nm to 500 nm. This radiation is longer in wavelength compared to the free exciton recombination radiation, and is not preferable for micro fabrication. Moreover, this radiation is clearly caused by impurities or lattice defects, so it is difficult to improve the radiation efficiency of the device and is disadvantageous when applied to practical use.

Moreover, Japanese Patent Laid-Open Publication No. 7-307487 discloses the spectrum of a light-emitting device, according to which the intensity of the free exciton recombination radiation (235 nm) being the radiation intrinsic to diamond is clearly smaller than (and less than half) the intensity of the bound exciton radiation (238 nm) being one example of radiation caused by impurities or defects.

In comparison, the diode-structure diamond light-emitting device according to the present invention provides the free



emission spectrum is 300 nm or smaller.

Claim 3 discloses a diode-structure diamond ultraviolet light-emitting device according to claim 1 or claim 2, wherein the diode-structure comprises a pn junction.

Claim 4 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 1, 2 or 3, wherein both diamond crystals are high-quality crystals including only a very small amount of impurity other than the dopant.

A dopant is a substance that is added intentionally to a diamond crystal so as to control the electric conductivity and the light emission property of the crystal. However, even when a dopant is added to the diamond crystal, in the diamond light-emitting device according to the present invention, the free exciton recombination radiation resulting from current injection is dominant.

Claim 5 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 1, 2, 3 or 4, wherein the n-type diamond crystal is a diamond crystal doped with phosphorous.

Claim 6 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 1, 2, 3 or 4, wherein the n-type diamond crystal is a diamond crystal doped with sulfur.

Claim 7 refers to a diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 6, wherein the n-type diamond crystal is a diamond crystal grown by the chemical vapor deposition (CVD) method.

Claim 8 refers to a diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 7, wherein the p-type semiconductor diamond crystal is a diamond crystal doped with boron.

Claim 9 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 8, wherein the boron-doped diamond crystal has a boron concentration of 100 ppm or smaller.

Claim 10 refers to a diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 9, wherein the p-type semiconductor diamond crystal is a crystal synthesized by the high temperature and high pressure method.

Claim 11 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 10, wherein the high-temperature and high-pressure synthetic diamond is synthesized by adding a nitrogen remover to the flux.

Claim 12 refers to a diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 9, wherein the p-type semiconductor diamond crystal is a diamond grown by CVD method.

Claim 13 refers to a diode-structure diamond ultraviolet light-emitting device according to any one of claims 7 through 12, wherein the CVD diamond crystal is a homoepitaxial film grown homoepitaxially on a diamond crystal substrate.

Claim 14 refers to a diode-structure diamond ultraviolet light-emitting device according to claim 7, 12 or 13, wherein









The actual structure of a diamond ultraviolet light-emitting device having a diode structure according to the first embodiment of the present invention, in which the free exciton recombination radiation is dominant and which is operated by current injection, is explained with reference to FIG. 1 and FIG. 2.

FIG. 1 (A) is a plan view showing a typical structure of a multiple light-emitting device 10, having a plurality of pn junction diode-structure diamond ultraviolet light-emitting devices on a single substrate in which the free exciton recombination radiation caused by current injection is dominant, and FIG. 1 (B) is a cross-sectional view thereof. FIG. 2 is a principle diagram showing in enlarged view one of the pn junction diode-structure diamond ultraviolet light-emitting devices 10 shown in FIG. 1, wherein all the light-emitting devices of FIG. 1 have the same structure shown in FIG. 2.

The pn junction diamond ultraviolet light-emitting device 10 realizing the free exciton recombination radiation comprises a p-type semiconductor layer 1 formed of boron-doped synthetic diamond p-type crystal obtained by the high temperature and high pressure method, a phosphorous-doped CVD diamond n-type crystal layer (n-type semiconductor layer) 3 grown on the surface of the p-type semiconductor layer 1 by the CVD method, a plurality of individual electrodes (first electrodes) 5 formed of tungsten (W) mounted on the growth surface of the phosphorous-doped CVD diamond n-type crystal layer 3, and one common electrode (second electrode) 7 formed of tungsten (W) mounted on the back surface

of the boron-doped high-pressure diamond p-type crystal layer (p-type semiconductor layer) 1.

Each individual electrode 5 is connected to an aluminum wire 51, and the common electrode 7 is connected to an aluminum wire 71.

A high quality diamond that does not include detectable lattice defects or impurities other than the dopant is used for the p-type semiconductor layer 1 and the n-type semiconductor layer 3.

In a IV group semiconductor such as diamond or silicon, it is common to add a II- III group element to provide a p-type electric conductivity, and to add a V-VI group element to provide an n-type electric conductivity. Examples of the p-type dopant for diamond include boron, and examples of the n-type dopant include phosphorous, sulfur and lithium.

The boron-doped synthetic diamond p-type crystal layer 1 that constitutes the pn junction diamond ultraviolet light-emitting device 10 for the free exciton recombination radiation is formed of a synthetic diamond crystal obtained by the high temperature and high pressure method explained below.

In this explanation, the high temperature and high pressure method refers to the so-called temperature difference method, and according to this diamond manufacturing method, carbon material is dissolved to flux metal and this carbon is deposited on a seed crystal (diamond microcrystal) in a temperature and pressure region under which diamond can exist stably.

The diamond manufacturing method utilizing the temperature difference method is disclosed for example in Japanese Patent Laid-Open Publication Nos. 4-108532 (108532/92) and 5-200271 (200271/93).

As for the flux metal, a material is used that is capable of sufficiently dissolving carbon and also works as a catalyst that accelerates the crystal growth of diamond. Actually, as disclosed in documents (for example, Kanda et al., Nippon Kagaku Kaishi (The Chemical Society of Japan), 1981, vol. 9, pp. 1349-1355), an alloy including iron (Fe) and/or cobalt (Co) and/or nickel (Ni) is used as the flux metal.

The boron-doped p-type synthetic diamond layer (p-type semiconductor layer) 1 is formed using the temperature difference method (the high temperature and high pressure method) and under the following conditions of growth.

[Conditions of growth]

Carbon material: pyrolysis carbon; doped with 3000 ppm of boron

Flux metal: iron (Fe) - cobalt (Co) alloy

Nitrogen remover: aluminum (Al), titanium (Ti), zirconium (Zr)

Growth temperature: 1450 °C

Synthesis pressure: 6.3 GPa

Growth time: 50 hours

In the list, nitrogen remover refers to a metal having higher affinity with nitrogen than carbon, and capable of reducing the nitrogen concentration in the diamond crystal when added to the flux metal. As disclosed in documents (for example, H. Sumiya

and S. Satho, Diam. Related Matter, Vol. 5, p. 1359 (1996)), the actual example includes Al, Ti and Zr.

Under the above-mentioned conditions, the seed crystal is placed so that the direction of growth is [001], and the crystal is synthesized. As a result, a blue-color single crystal having a facet of {100} and {111} weighing 64.0 mg is created.

The formed crystal is cleaved along the (111) surface, and is polished into a plate-like shape with a thickness of 0.5 mm and a size of 1 mm x 2 mm using a skeif grinder.

The boron concentration in the crystal is measured using an infrared absorption spectroscopy (refer to R. M. Cherenko, M. Strong and R. E. Tuft, Phil. Mag., vol. 23, p. 313, 1971). The infrared (IR) absorption spectrum of the sample is measured using a micro IR apparatus, and the absorbance  $a_1$  at a wave number of 1280 [1/cm] or the absorbance  $a_2$  at a wave number of 2800 [1/cm] is computed. The former is effective if the boron concentration in the crystal is 10 ppm or more, and the latter is effective when the concentration is less than 10 ppm. The conversion formula of the former and latter values is represented by the following equation (1).

$$a_2/a_1 = 22 \quad \dots (1)$$

When the film thickness is represented by  $d$  [cm], the effective acceptor concentration  $N_A$  (of the boron included in the crystal, the concentration of boron atoms being active acceptors) within the crystal can be calculated by the following equation (2). When this method is applied, the effective

acceptor concentration within the crystal is calculated as 9 ppm.

Further, since no absorption peak related to nitrogen (1130, 1185, 1282, 1370 [1/cm]) is observed according to the IR spectrum measurement, the nitrogen concentration within the crystal is calculated as 0.1 ppm or less.

$$N_A \text{ [ppm]} = 0.086 \times a_1/d \quad \dots (2)$$

A phosphorous-doped n-type diamond layer 3 being grown homoepitaxially by MW-CVD method is grown on this boron-doped p-type diamond layer 1.

The homoepitaxial growth of the n-type diamond layer 3 is performed by an MW-CVD apparatus and using a high-grade methane gas and a high-grade hydrogen gas and under the following conditions.

Upon growth, the sample surface is cleaned by performing H<sub>2</sub> plasma processing for 10 minutes.

[Conditions of growth]

Substrate: boron-doped p-type synthetic diamond

MW output: 600 W

Gas: CH<sub>4</sub>; 0.0125%, H<sub>2</sub>; 99.9875%

Phosphorous source: trimethyl phosphorous (P(CH<sub>3</sub>)<sub>3</sub>)

P/C ratio: 2200 ppm

Gas purity: CH<sub>4</sub>; 99.9999%, H<sub>2</sub>; 99.99999%

Flow rate: 200 ml/min

Synthesis pressure: 40 Torr

Temperature: 900 – 950 °C

Growth time: 50 hours

The thickness of the CVD diamond n-type crystal layer is 0.7  $\mu\text{m}$ . Since a hydrogen termination conductive layer is generally formed on the surface of the diamond formed by the CVD method, the sample is treated in a chromic acid mixture for 10 minutes so as to insulate the diamond surface.

Then, first electrodes 5 made of tungsten is formed on the phosphorous-doped n-type CVD diamond film (n-type semiconductor layer) 3 through sputtering.

[Conditions for sputtering]

Target: tungsten (W)

Gas flow rate: Ar; 30 ml/min

Pressure: 5 mTorr

Substrate temperature: 200  $^{\circ}\text{C}$

Voltage: 700 V

Current: 1 A

Time: 4 min

Thickness: 300  $\text{\AA}$

Next, a positive photoresist layer is formed on the tungsten layer (first electrode) 5 by spin coating and the like (photoresist viscosity: 15 Cp, revolution: 3,500 rpm, time: 30 sec), which is dried under atmosphere at 80  $^{\circ}\text{C}$  for 30 minutes, and then unnecessary portions are exposed to ultraviolet using a mask aligner (ultraviolet exposure: 350  $\text{mJ}/\text{cm}^2$ ), the exposed portions being removed using a photoresist developer, and it is dried in atmosphere at 130  $^{\circ}\text{C}$  for 30 minutes, thereby creating

the resist film.

The resist film is used to perform etching of the tungsten layer using aqua regia (hydrochloric acid: nitric acid = 3:1) for three minutes.

Thereafter, acetone is used to perform ultrasonic cleaning for three minutes, so as to remove the resist and to fabricate electrodes 5.

On the back surface of the boron-doped p-type synthetic diamond layer 1, a second electrode 7 is formed using tungsten in a similar manner, thereby completing the pn junction diamond ultraviolet light-emitting device 10 using CVD diamond.

FIG. 3 is referred to in explaining the current-voltage characteristic of the pn junction diamond ultraviolet light-emitting diode 10 utilizing the CVD diamond crystal formed as explained, that realizes the free exciton recombination radiation. In FIG. 3, the horizontal axis represents the voltage (V) applied between the first electrode 5 and the second electrode 7, and the vertical axis represents the current ( $\mu\text{A}$ ) flowing from the first electrode 5 to the second electrode 7.

As is clearly shown in the drawing, when a reverse bias voltage is applied so that the potential of the first electrode 5 becomes positive, the leakage current is  $0.01\mu\text{A}$  or smaller until the voltage exceeds 20 V. When a forward bias voltage is applied where the first electrode 5 becomes negative, the current increases greatly from about -12 V. This result shows that a diode characteristic is obtained by the pn junction

structure of the present device.

FIG. 4 is referred to in explaining the result of measurement of the current injection emission spectrum.

FIG. 4 shows the result of measurement of the light emitted when 80 V of voltage is applied between the electrodes and 1 mA of current flows therethrough, wherein the horizontal axis represents the wavelength (nm) and the vertical axis represents the emission intensity (arbitrary scale).

As clearly shown in FIG. 4, the emission advantageously shows a main peak at around 235 nm in the ultraviolet region, and a minor peak at around 242 nm. These two peaks are both obtained by the free exciton recombination radiation. On the other hand, in the wavelength range of under 300 nm, there are no other emission peaks such as a boron bound exciton recombination radiation (238 nm) observed.

Therefore, according to the present invention, the ultraviolet radiation caused by current injection shows a strong free exciton recombination radiation having a high efficiency, and includes very weak radiation caused by impurities/lattice defects having low efficiency, so it can be concluded that according to the invention a diode-structure diamond ultraviolet light-emitting device is obtained that realizes the free exciton recombination radiation having a high emission efficiency.

Now, according to a second embodiment of the present invention, the actual composition of a diode-structure diamond ultraviolet light-emitting device activated by current



injection in which the free exciton recombination radiation is dominant is explained with reference to FIG. 1 and FIG. 2, the same drawings that were referred to in the first embodiment.

The pn junction diamond ultraviolet light-emitting device 10 that realizes the free exciton recombination radiation comprises a p-type semiconductor layer 1 formed of boron-doped p-type synthetic diamond formed by the high temperature and high pressure method, a sulfur-doped n-type CVD diamond layer (n-type semiconductor layer) 3 grown on the surface of the p-type semiconductor layer 1 by the CVD method, a plurality of individual electrodes (first electrodes) 5 made of titanium (Ti) mounted on the growing surface of the sulfur-doped n-type CVD diamond layer 3, and one common electrode (second electrode) 7 made of titanium (Ti) formed on the back surface of the boron-doped p-type synthetic diamond layer (p-type semiconductor layer) 1.

Each individual electrode 5 is connected to an aluminum wire 51, and the common electrode 7 is connected to an aluminum wire 71.

A high quality diamond that does not include detectable lattice defects or impurities other than the dopant is used for the p-type semiconductor layer 1 and the n-type semiconductor layer 3.

The boron-added high pressure diamond p-type crystal layer (p-type semiconductor layer) 1 is manufactured by a temperature difference method (high temperature and high pressure method) under the following conditions of growth.

[Conditions of growth]

Carbon material: pyrolysis carbon; 1000 ppm of boron is added as dopant

Flux metal: iron (Fe) - cobalt (Co) alloy

Nitrogen remover: aluminum (Al), titanium (Ti), zirconium (Zr)

Growth temperature: 1450 °C

Synthetic pressure: 6.3 GPa

Growth time: 80 hours

Under the above-mentioned conditions, the seed crystal is placed so that the direction of growth is [001], and the crystal is synthesized. As a result, a blue-color single crystal having a facet of {100} and {111} weighing 81.1 mg is created.

The formed crystal is polished into a plate-like shape having the (001) surface as the upper and lower surfaces with a thickness of 0.5 mm and a size of 1 mm x 2 mm using a skeif grinder.

The boron concentration of the crystal is measured using IR absorption spectroscopy similar to the first embodiment, and as a result, the effective acceptor concentration within the crystal is calculated as 1.4 ppm.

Further, since no absorption peak related to nitrogen (1130, 1185, 1282, 1370 [1/cm]) was observed according to the IR spectrum measurement, the nitrogen concentration within the crystal measured by the IR absorption spectroscopy is calculated as 0.1 ppm or less.

$$NA \text{ [ppm]} = 0.086 \times a/d \quad \dots (2)$$

A sulfur-doped n-type diamond layer 3 is grown

homoepitaxially by the MW-CVD method on the boron-doped p-type diamond layer 1.

The homoepitaxial growth of the n-type diamond layer 3 is performed using an MW-CVD apparatus and with a high-grade methane gas and a high-grade hydrogen gas and under the following conditions.

Upon growth, the sample surface is cleaned by performing H<sub>2</sub> plasma processing for 10 minutes.

[Conditions of growth]

Substrate: boron-doped synthetic diamond crystal

MW output: 500 W

Gas: CH<sub>4</sub>; 1%, H<sub>2</sub>; 99%

Sulfur source: hydrogen sulfide (H<sub>2</sub>S)

S/C ratio: 5000 ppm

Gas purity: CH<sub>4</sub>; 99.9999%, H<sub>2</sub>; 99.9999%

Flow rate: 100 ml/min

Synthesis pressure: 40 Torr

Temperature: 900 °C

Growth time: 100 min

The thickness of the sulfur-doped n-type CVD diamond layer is 1 μm. The sample is processed by chromic acid mixture for 10 minutes so as to insulate the surface.

Then, first electrodes 5 made of titanium is formed on the sulfur-doped n-type CVD diamond film (n-type semiconductor layer) 3 through sputtering.

[Conditions for sputtering]

Target: titanium (Ti)  
 Gas flow rate: Ar; 30 ml/min  
 Pressure: 5 mTorr  
 Substrate temperature: 200 °C  
 Voltage: 700 V  
 Current: 1 A  
 Time: 4 min  
 Thickness: 500 Å

Next, a resist film is formed on the titanium layer (first electrode) 5 in a manner similar to the first embodiment.

The resist film is used to perform etching of the titanium layer using fluoroboric acid for five seconds.

Thereafter, acetone is used to perform ultrasonic cleaning for three minutes, so as to remove the resist and to fabricate electrodes 5.

On the back surface of the boron-doped p-type synthetic diamond layer 1, a second electrode 7 is formed using titanium in a similar manner, so as to complete the pn junction diamond ultraviolet light-emitting device 10 using CVD diamond crystal.

FIG. 5 is referred to in explaining the current-voltage characteristic of the pn junction diamond ultraviolet light-emitting diode 10 utilizing the CVD diamond formed as explained above that realizes the free exciton recombination radiation. In FIG. 5, the horizontal axis shows the voltage (V) applied between the first electrode 5 and the second electrode 7, and the vertical axis shows the current ( $\mu$ A) flowing from

the first electrode 5 to the second electrode 7.

As is clearly shown in the drawing, when a reverse bias voltage is applied so that the potential of the first electrode 5 becomes positive, the leakage current is  $0.01\mu\text{A}$  or smaller until the voltage exceeds 20 V. When a forward bias voltage is applied by which the first electrode 5 becomes negative, the current increases greatly from about -10 V. This result shows that a diode characteristic is obtained by the pn junction structure of the present device.

FIG. 6 is referred to in explaining the result of measurement of the current injection emission spectrum.

FIG. 6 shows the result of measurement of the light emitted when 70 V of voltage is applied between the electrodes and  $50\mu\text{A}$  of current flows therethrough, wherein the horizontal axis represents the wavelength (nm) and the vertical axis represents the emission intensity (arbitrary scale).

As clearly shown in FIG. 6, the emission advantageously shows a main peak at around 235 nm in the ultraviolet region, and a minor peak at around 242 nm. These two peaks are both results of the free exciton recombination radiation. On the other hand, in the wavelength range of under 300 nm, there are no other emission peaks such as a boron bound exciton recombination radiation (238 nm) observed.

Therefore, according to the second embodiment, the ultraviolet radiation caused by current injection shows a strong free exciton recombination radiation having high efficiency,

and shows only weak radiation caused by impurities/lattice defects having low efficiency, so it can be concluded that a diode structure diamond ultraviolet light-emitting device is obtained that realizes the free exciton recombination radiation having high emission efficiency.

The influence that the boron concentration within the p-type diamond crystal 1 has against ultraviolet emission property according to the diode structure diamond ultraviolet light-emitting device 10 of the present invention is studied, the result of which explained with reference to Table 1.

The device formed according to the first embodiment of the invention is used as example 1, and the pn junction diamond light-emitting device according to example 2 and that of the comparison example 1 is manufactured under the same conditions as example 1, except for the amount of boron being added when fabricating the p-type boron-doped high pressure crystal. Further, the device fabricated according to the second embodiment is used as example 3. The amount of boron being added to the p-type crystal of each example is as listed below, showing the amount of boron being added to the material carbon (ppm).

Example 1 (phosphorous-doped n-type crystal):

Amount of added boron; 3000 ppm

Example 2 (phosphorous-doped n-type crystal):

Amount of added boron; 30000 ppm

Example 3 (sulfur-doped n-type crystal):

Amount of added boron; 1000 ppm

Comparison example (phosphorous-doped n-type crystal):

Amount of added boron; 100000 ppm

Table 1

Device	Boron concentration measured by SIMS method (ppm)	Free exciton recombination radiation by current injection
Example 1	6.0	yes
Example 2	88	yes
Example 3	0.44	yes
Comparison example 1	150	no

According to the device of example 2 the free exciton recombination radiation is observed, but according to the device of comparison example 1 no free exciton recombination radiation is observed.

As a result of measuring the boron concentration of the p-type diamond layer of the devices according to example 1, example 2, example 3 and comparison example 1 respectively by secondary ion mass spectroscopy (SIMS), a value of 6.0, 88, 0.44 and 150 ppm is obtained. Therefore, it is understood that in order to obtain the free exciton recombination radiation, the maximum boron concentration is approximately 100 ppm.

As explained, the present invention enables to provide a diode-structure diamond ultraviolet light-emitting device utilizing a CVD diamond crystal in which the free exciton

recombination radiation based on current injection is dominant.

Now, FIG. 7 is referred to in explaining the actual structure of a third embodiment of the present invention, which is a diode-structure diamond ultraviolet light-emitting device activated by current injection in which the free exciton recombination radiation is dominant.

The pn junction diamond ultraviolet light-emitting device 10 realizing the free exciton recombination radiation according to the third embodiment comprises an insulative substrate 30 formed of diamond monocrystal synthesized by the high temperature and high pressure synthesis method, a boron-doped p-type CVD diamond layer (p-type semiconductor layer) 31 grown on the surface of the insulative substrate 30 by the CVD method, a sulfur-doped n-type CVD diamond layer (n-type semiconductor layer) 33 grown selectively on a portion of the CVD surface of the boron-doped p-type CVD diamond layer (p-type semiconductor layer) 31 by the CVD method, a first electrode 35 made of titanium (Ti) and gold (Au) mounted on a portion of the surface of the boron-doped p-type CVD diamond layer 31, and a second electrode 37 made of titanium (Ti) and gold (Au) formed on the CVD growth surface of the sulfur-doped n-type CVD diamond layer 33.

The first electrode 35 and the second electrode 37 are each connected to an aluminum wire 51.

A high quality diamond that does not include detectable lattice defects or impurities other than the dopant is used for the p-type semiconductor layer 31 and the n-type





by the MW-CVD method selectively only to the remaining exposed portion.

The homoepitaxial growth of the n-type CVD diamond layer 33 is performed using a MW-CVD apparatus and with a highly pure methane gas and a highly pure hydrogen gas and under the following conditions.

Upon growth, the sample surface is cleaned by performing H<sub>2</sub> plasma processing thereto for 10 minutes.

[Conditions of growth]

Substrate: boron-doped CVD diamond crystal

MW output: 500 W

Gas: CH<sub>4</sub>; 1.0%, H<sub>2</sub>; 99%

Sulfur source: hydrogen sulfide (H<sub>2</sub>S)

S/C ratio: 5000 ppm

Gas purity: CH<sub>4</sub>; 99.9999%, H<sub>2</sub>; 99.9999%

Flow rate: 100 ml/min

Synthesis pressure: 40 Torr

Temperature: 900 °C

Growth time: 100 min

Film thickness: 1.0 μm

The thickness of the sulfur-doped n-type CVD diamond layer 33 is 1 μm. The sample is processed by chromic acid mixture for 10 minutes so as to insulate the surface.

Then, the diamond mask formed on the boron-doped p-type CVD diamond layer (p-type semiconductor layer) 31 is removed, and electrodes 35 and 37 made of Au/Ti are respectively formed

by sputtering on the exposed surface of the boron-doped p-type CVD diamond layer (p-type semiconductor layer) 31 and on the appropriate position on the surface of the sulfur-doped n-type CVD diamond layer 33. The electrodes 35 and 37 are fabricated first by forming a layer of titanium (Ti) on the diamond crystal layer 31 and 33, and then forming a layer of gold (Au) on the top.

[Conditions for sputtering 1]

Target: titanium (Ti)

Gas flow rate: Ar; 30 ml/min

Pressure: 5 mTorr

Substrate temperature: 200 °C

Voltage: 700 V

Current: 1 A

Time: 4 min

Thickness: 500 Å

[Conditions for sputtering 2]

Target: gold (Au)

Gas flow rate: Ar; 30 ml/min

Pressure: 5 mTorr

Substrate temperature: 200 °C

Voltage: 700 V

Current: 1.5 A

Time: 10 min

Thickness: 500 Å

Next, a resist film is formed on the gold layer in a manner

similar to the first embodiment.

The resist film is used to perform etching of the gold layer and the titanium layer using fluoroboric acid for five seconds.

Thereafter, acetone is used to perform ultrasonic cleaning for three minutes, so as to remove the resist and to fabricate electrode 5.

According to the above steps, the pn junction diamond ultraviolet light-emitting device 10 utilizing a synthetic diamond crystal is manufactured.

FIG. 8 is referred to in explaining the current-voltage characteristic of the pn junction diamond ultraviolet light-emitting device 10 utilizing the CVD diamond crystal formed as explained above that realizes the free exciton recombination radiation. In FIG. 8, the horizontal axis represents the voltage (V) applied between the first electrode 35 and the second electrode 37, and the vertical axis represents the current ( $\mu$  A) flowing from the first electrode 35 to the second electrode 37.

As is clearly shown in the drawing, when a reverse bias voltage is applied so that the potential of the first electrode 35 becomes positive, the leakage current is 10 pA or smaller until the voltage exceeds 20 V. When a forward bias voltage is applied by which the first electrode 35 becomes negative, the current increases greatly from about -15 V. This result shows that a diode characteristic is obtained by the pn junction structure of the present device.

FIG. 9 is referred to in explaining the result of measurement of the current injection emission spectrum.

FIG. 9 shows the result of measurement of the light emitted when 50 V of forward voltage is applied between the two electrodes and 1 mA of current flows therethrough, wherein the horizontal axis represents the wavelength (nm) and the vertical axis represents the emission intensity (arbitrary scale).

As clearly shown in FIG. 9, the emission advantageously shows a main peak at around 235 nm in the ultraviolet region resulting from the free exciton recombination radiation, and a minor peak at around 242 nm. These two peaks are both obtained by the free exciton recombination radiation. On the other hand, in the wavelength range of under 300 nm, there are no other emission peaks such as a boron-related bound exciton recombination radiation (238 nm) observed.

Therefore, according to the third embodiment, the ultraviolet radiation caused by current injection shows a strong free exciton recombination radiation having a high efficiency, and includes very weak radiation caused by impurities/lattice defects having low efficiency, so it can be concluded that a diode structure diamond ultraviolet light-emitting device is obtained that realizes the free exciton recombination radiation having a high emission efficiency.

According to the third embodiment, the first CVD semiconductor diamond layer formed above the synthetic diamond crystal is a p-type semiconductor layer, and an n-type

semiconductor layer formed of a second CVD diamond layer is grown thereon, but according to another example of the invention, the first CVD semiconductor diamond layer formed on the synthetic diamond crystal can be an n-type semiconductor layer, and the second CVD semiconductor diamond layer formed thereon can be a p-type semiconductor layer.

#### Industrial applicability

As explained, the diode-structure diamond ultraviolet light-emitting device realizing the free exciton recombination radiation according to the present invention is capable of generating a short-wavelength ultraviolet radiation resulting from current injection.

We claim:

1. A diode-structure diamond ultraviolet light-emitting device, said device comprising a p-type semiconductor layer formed of diamond crystal, and an n-type semiconductor layer formed of diamond crystal, said device emitting light when excited by current injection, and wherein the free exciton recombination radiation is dominant.

2. A diode-structure diamond ultraviolet light-emitting device according to claim 1, wherein said the free exciton recombination radiation being dominant refers to a state where the intensity of the free exciton recombination radiation is at least two times or more greater than the intensity of radiation caused by impurities or defects, in the range where the wavelength of the current injection emission spectrum is 300 nm or smaller.

3. A diode-structure diamond ultraviolet light-emitting device according to claim 1 or claim 2, wherein said diode-structure diamond ultraviolet light-emitting device comprises a pn junction.

4. A diode-structure diamond ultraviolet light-emitting device according to claim 1, 2 or 3, wherein both said diamond crystals are high-quality crystals including only a minute amount of impurity other than the dopant.

5. A diode-structure diamond ultraviolet light-emitting device according to claim 1, 2, 3 or 4, wherein said n-type diamond crystal is a diamond crystal doped with phosphorous.

6. A diode-structure diamond ultraviolet light-emitting device according to claim 1, 2, 3 or 4, wherein said n-type diamond crystal is a diamond crystal doped with sulfur.

7. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 6, wherein said n-type diamond crystal is a diamond crystal grown by the chemical vapor deposition method.

8. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 7, wherein said p-type semiconductor diamond crystal is a diamond crystal doped with boron.

9. A diode-structure diamond ultraviolet light-emitting device according to claim 8, wherein said boron-doped diamond crystal has a boron concentration of 100 ppm or smaller.

10. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 9, wherein said p-type semiconductor diamond crystal is a crystal synthesized by the high temperature and high pressure synthesis method.



11. A diode-structure diamond ultraviolet light-emitting device according to claim 10, wherein said high-temperature and high-pressure synthetic diamond crystal is synthesized by adding a nitrogen remover to the flux.

12. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 9, wherein said p-type semiconductor diamond crystal is a diamond crystal grown by the chemical vapor deposition method.

13. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 7 through 12, wherein said diamond crystal grown by the chemical vapor deposition method is a homoepitaxial film grown homoepitaxially on a diamond crystal substrate.

14. A diode-structure diamond ultraviolet light-emitting device according to claim 7, claim 12 or claim 13, wherein said diamond crystal grown by chemical vapor deposition method is a diamond crystal film grown by the microwave plasma-assisted chemical vapor deposition method.

15. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 11, said device comprising a p-type semiconductor diamond crystal synthesized

by the high temperature and high pressure synthesis method, and a n-type diamond crystal grown on said p-type semiconductor diamond crystal by the chemical vapor deposition method.

16. A diode-structure diamond ultraviolet light-emitting device according to any one of claims 1 through 9 or claims 12 through 15, wherein a first diamond crystal grown by the chemical vapor deposition method is formed on a diamond substrate, and a second diamond crystal grown by the chemical vapor deposition method is further formed thereon.

17. A diode-structure diamond ultraviolet light-emitting device according to claim 16, wherein said first diamond crystal grown by the chemical vapor deposition method is either a p-type semiconductor diamond crystal or an n-type semiconductor diamond crystal, and said second diamond crystal grown by the chemical vapor deposition method is either an n-type semiconductor diamond crystal or a p-type semiconductor diamond crystal that differs from the first diamond crystal grown by the chemical vapor deposition method.

18. A diode-structure diamond ultraviolet light-emitting device according to claim 16 or 17, wherein said second diamond layer grown by the chemical vapor deposition method is grown selectively on said first diamond layer grown by the chemical vapor deposition method.

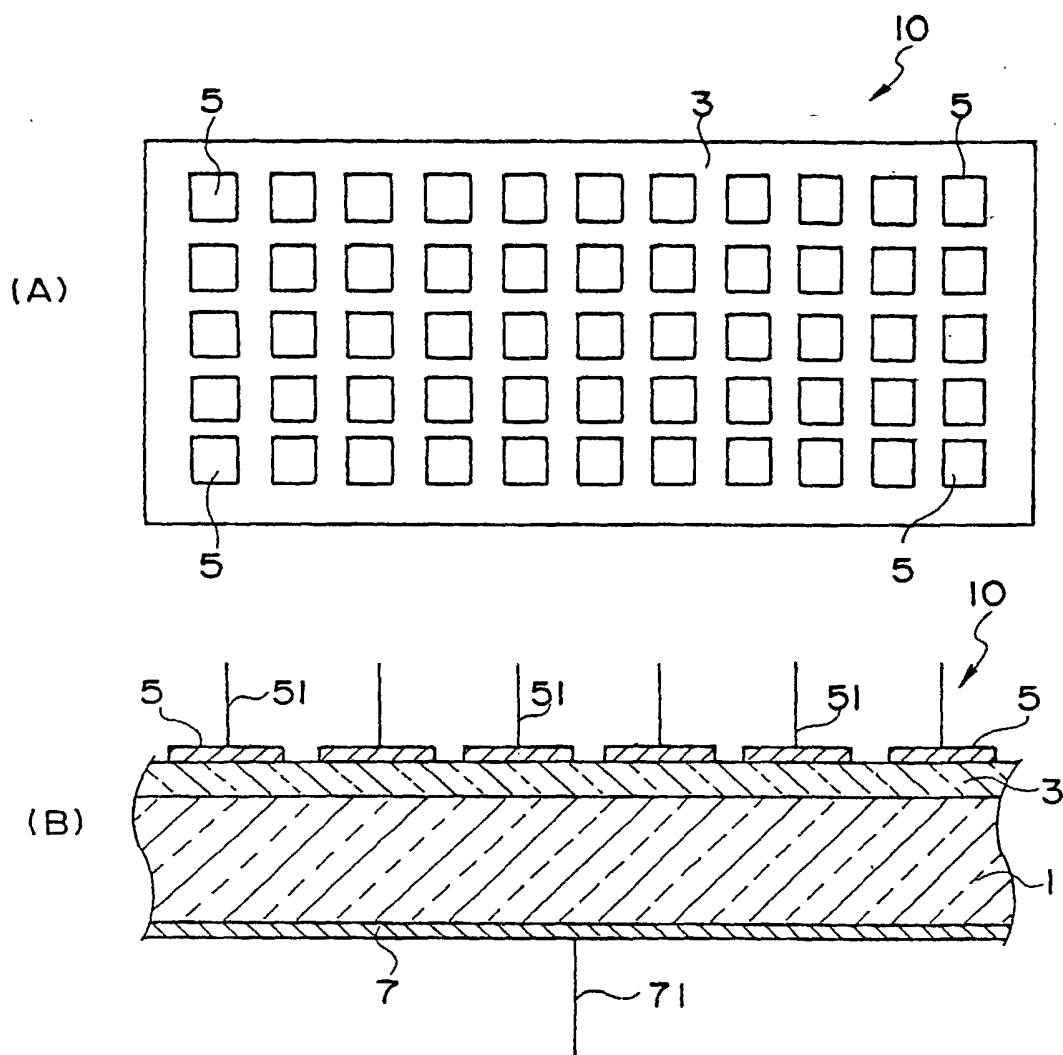
19. A diode-structure diamond ultraviolet light-emitting device according to claim 16, 17 or 18, wherein an electrode is formed on the exposed surface of said first diamond layer grown by the chemical vapor deposition method.

## ABSTRACT

A diamond ultraviolet luminescent element (10) having a current-injection light-emitting diode structure includes a high-quality boron-doped p-type diamond crystal (semiconductor layer) (1) synthesized by the high pressure and high temperature method; a phosphorous-doped n-type diamond crystal (n-type semiconductor layer) (3) formed on the first diamond surface by the chemical vapor deposition; an electrode (5) formed on the surface of the n-type semiconductor layer (3); and an electrode (7) formed on the surface of the p-type semiconductor layer (1). The luminescence (235nm) attributed to the recombination of free excitons resulting from current injection dominates in ultraviolet wavelength region (10).

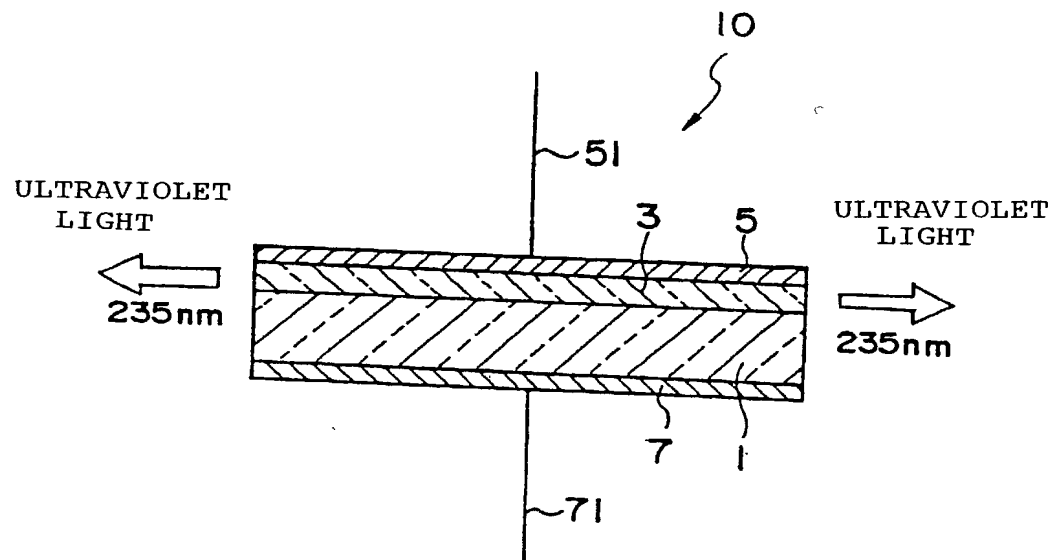
1/9

Fig. 1



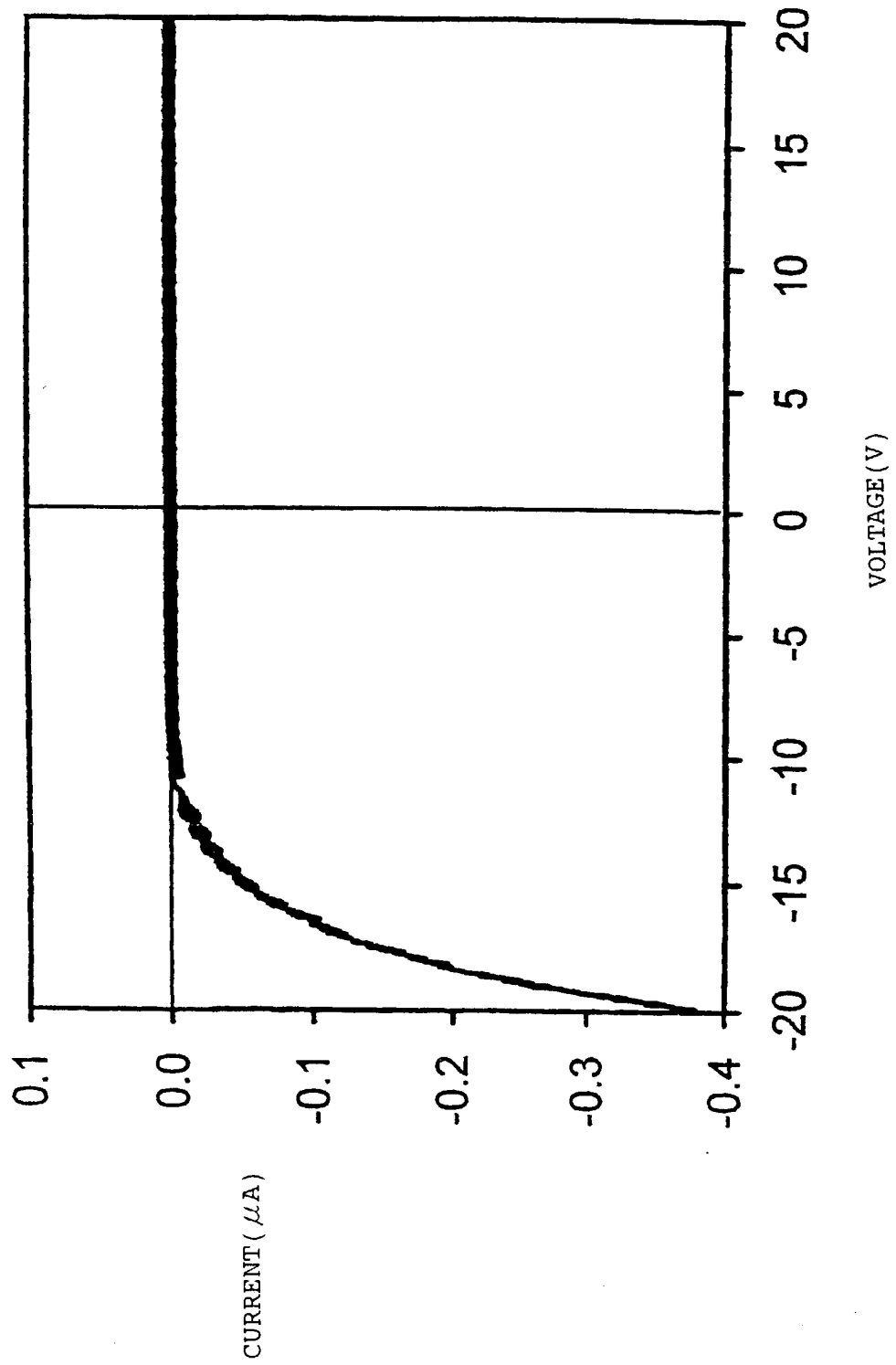
2/9

Fig. 2



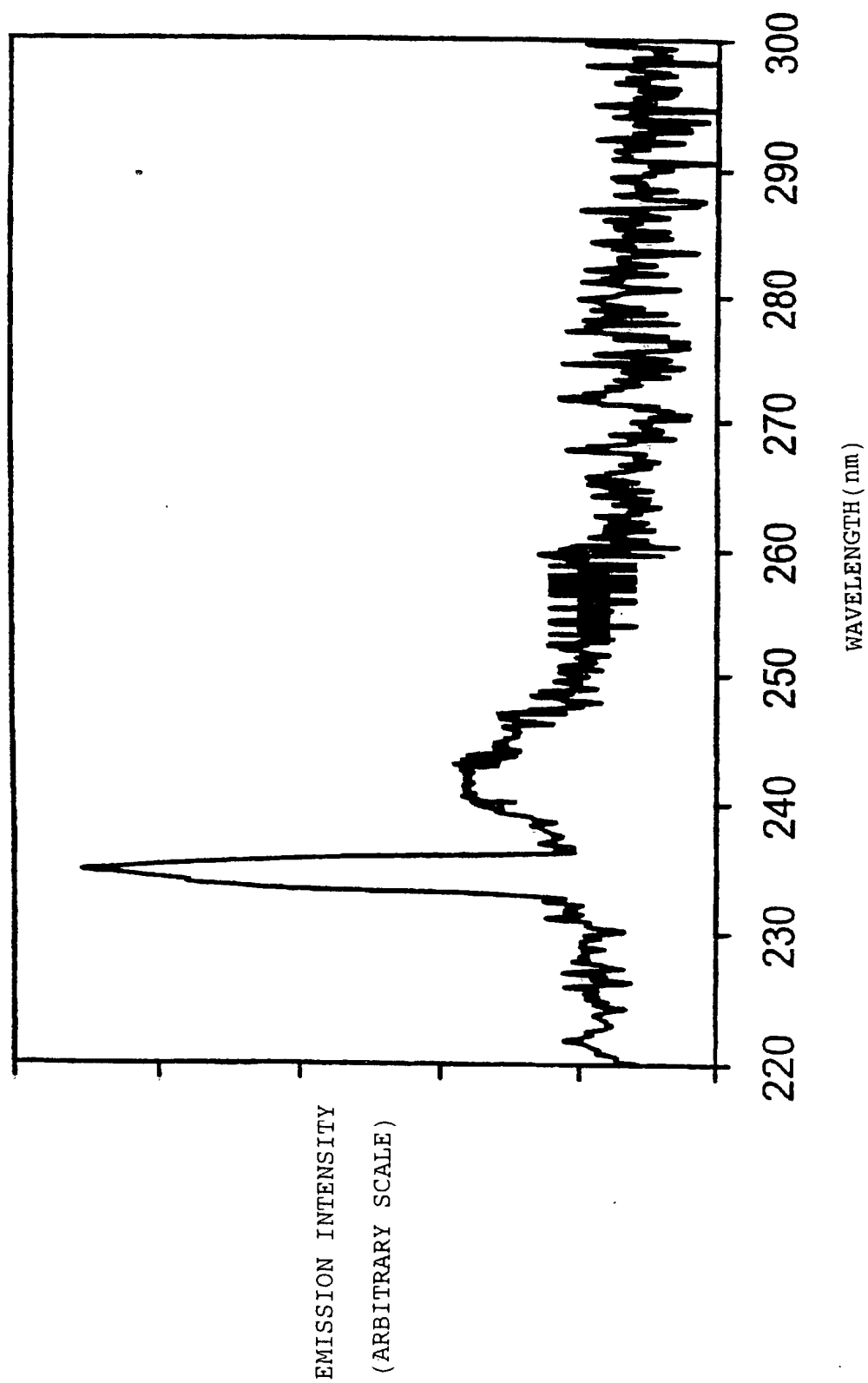
3/9

Fig. 3



4/9

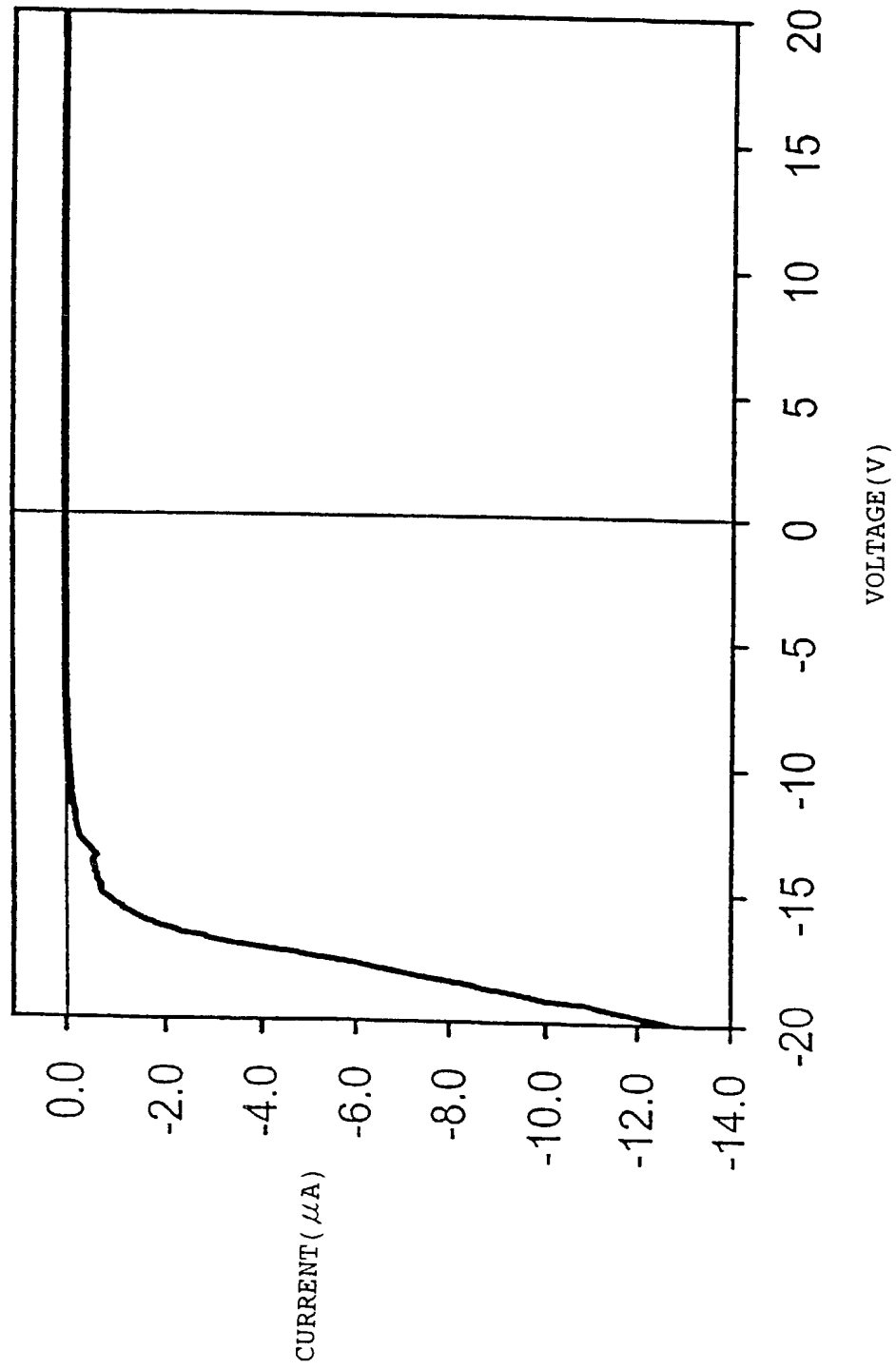
Fig. 4





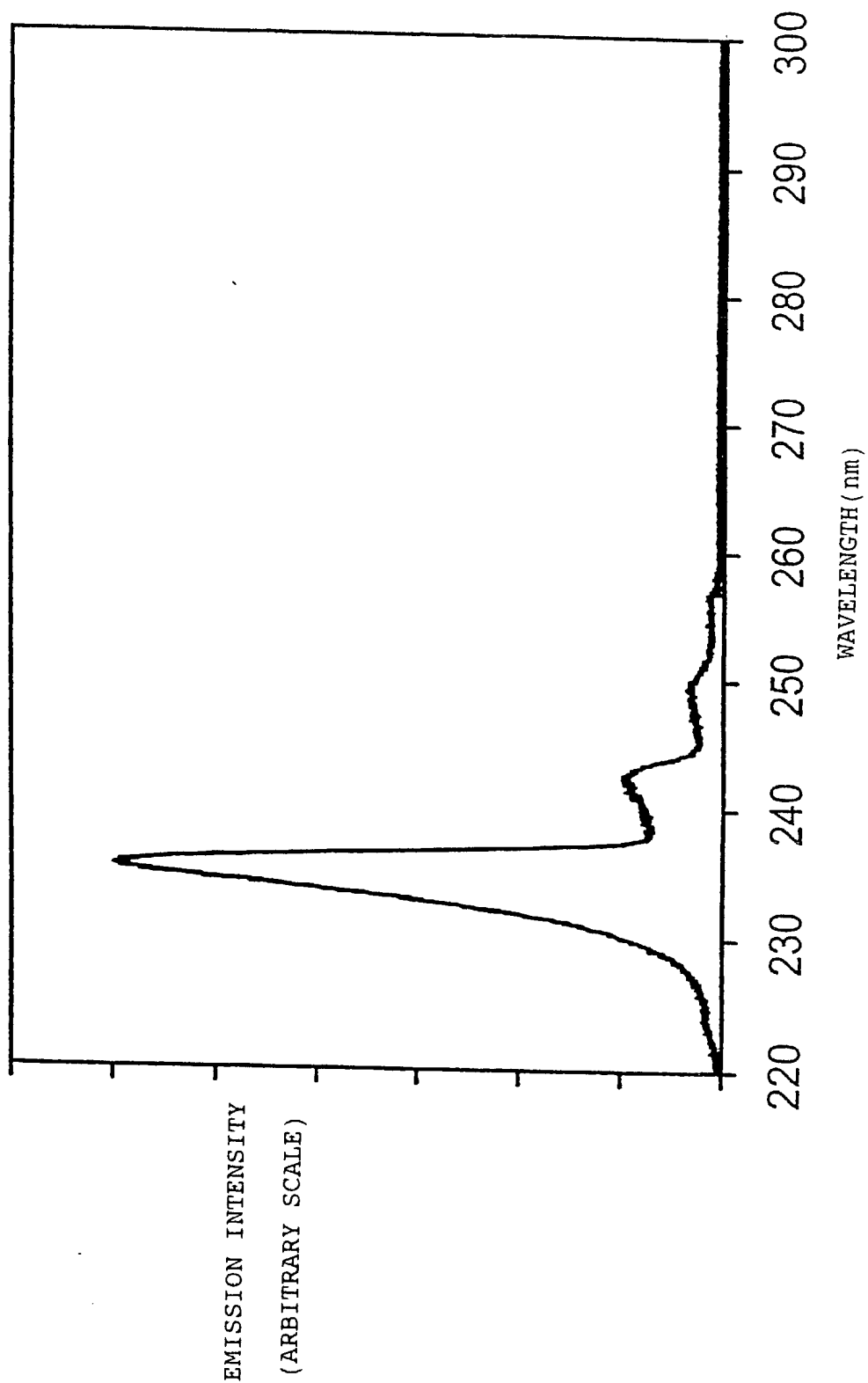
5/9

Fig. 5



6/9

Fig. 6



7/9

Fig. 7

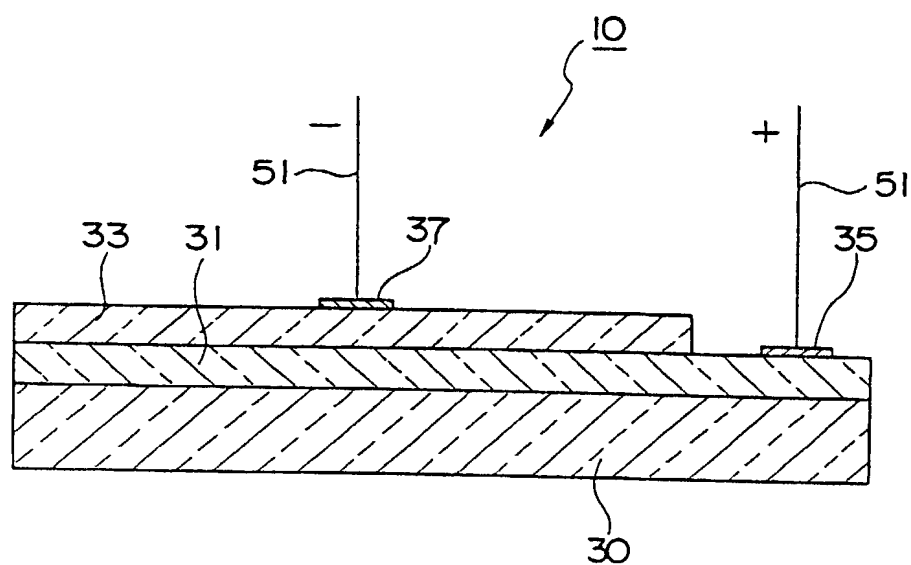
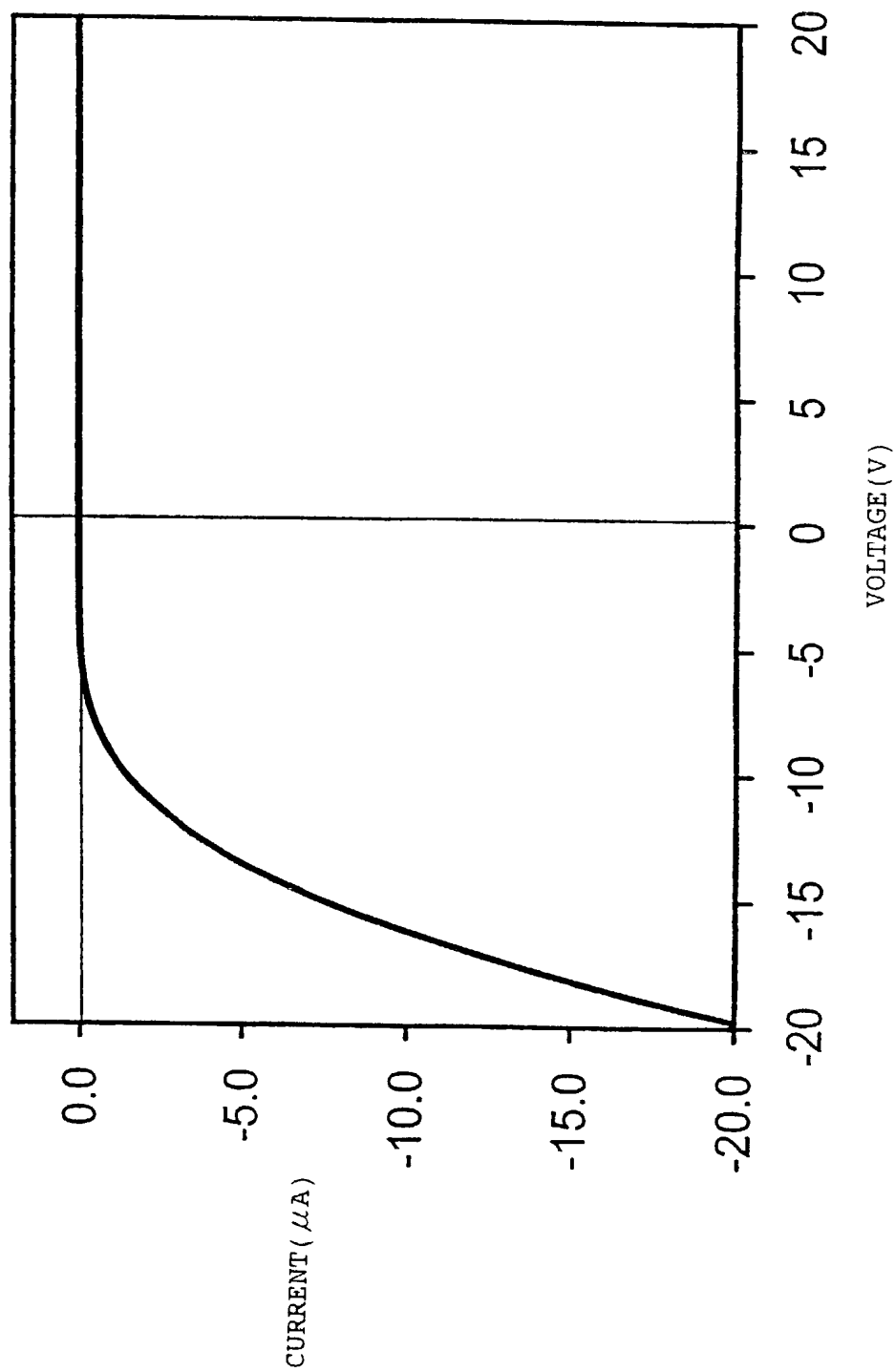
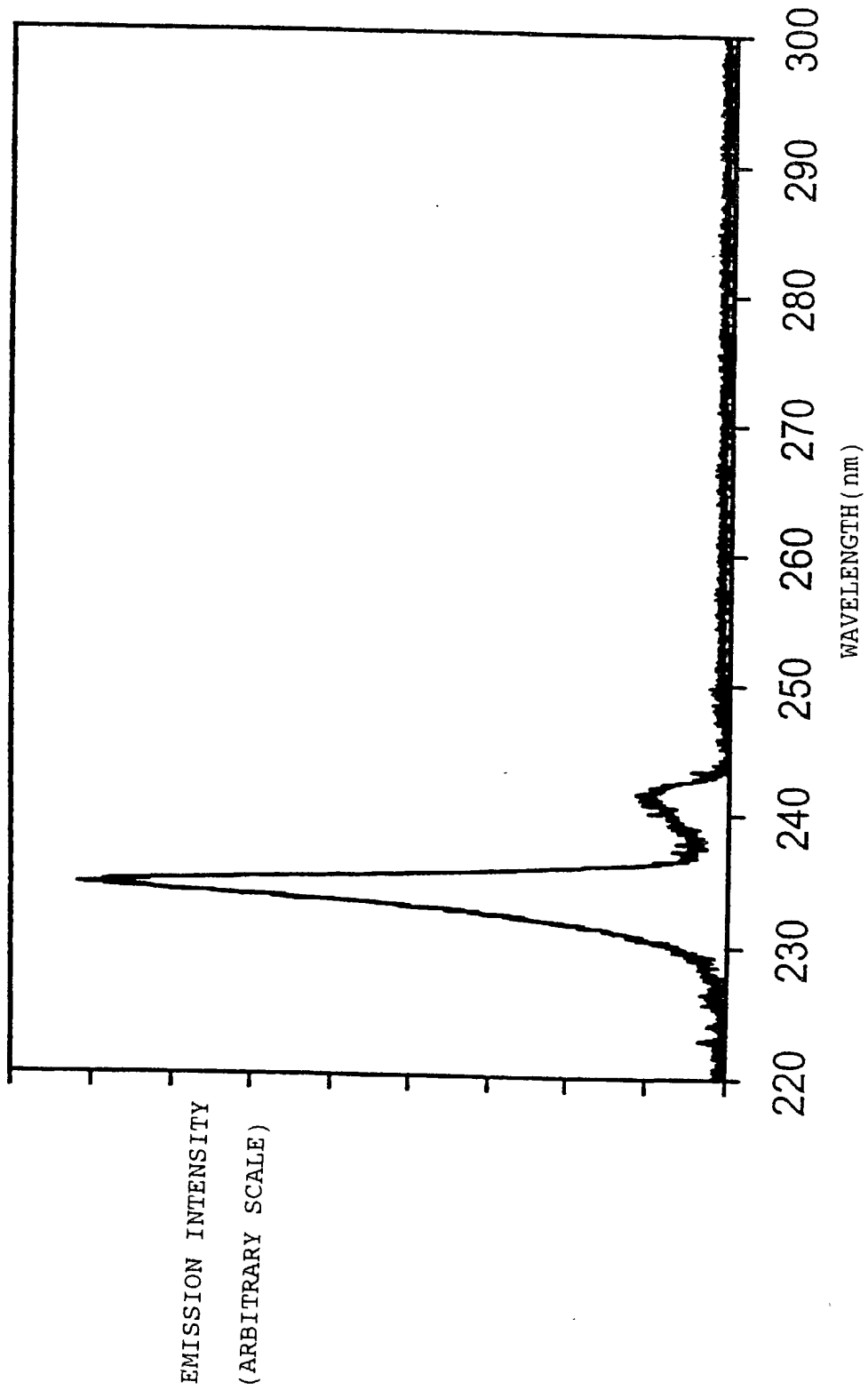


Fig. 8



9/9

Fig. 9



**Declaration For U.S. Patent Application**PCT/JP00/04301  
(6246PCT)

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention **entitled**  
(Insert Title) DIAMOND ULTRAVIOLET LUMINESCENT ELEMENT

the specification of which is attached hereto unless the following is checked:



was filed on June 29, 2000 as United States Application Number or PCT International  
Application Number PCT/JP00/04301 and was amended on \_\_\_\_\_  
(if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claim(s), as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, § 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 (a) - (d) of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

(List prior foreign applications. See note A on back of this page)	<u>H11-192554</u> (Number)	<u>Japan</u> (Country)	<u>07/July/1999</u> (Day/Month/Year Filed)	Priority Claimed <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	<u>2000-032096</u> (Number)	<u>Japan</u> (Country)	<u>09/February/2000</u> (Day/Month/Year Filed)	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	<input type="checkbox"/> Yes <input type="checkbox"/> No
	_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	<input type="checkbox"/> Yes <input type="checkbox"/> No

(See note B on back of this page)

☐ See attached list for additional prior foreign applications

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below.

_____ (Application Number)	_____ (Filing Date)
_____ (Application Number)	_____ (Filing Date)

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, § 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, § 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of the application:

(List Prior U.S. Applications)	_____ (Application Serial Number)	_____ (Filing Date)	_____ (Status) (patented, pending, abandoned)
	_____ (Application Serial Number)	_____ (Filing Date)	_____ (Status) (patented, pending, abandoned)

I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18 of the United States Code, § 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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C above)

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